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Static Characterized Hybrid Wireless Mesh Protocol for Smart Grid Neighbourhood Area Networks

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Abstract—Smart Grid neighbourhood area networks (NANs), involving wide coverage and huge number of devices, are required to provide reliable communications for supporting various applications. The IEEE 802.11s standard based wireless mesh network associated with hybrid wireless mesh protocol (HWMP) is highly recommended due to its extended functionality. However, the HWMP based mesh networks can not guarantee quality of service (QoS) for each user which is a critical issue in Smart Grid communications. In this paper, we show the impact of the intermittent route unavailable problem and propose a static characterized HWMP which aims to mitigate the problem by taking advantage of the static characteristic of Smart Grid networks. The proposed scheme combines two methods, an extended routing table and a historical path selection algorithm. A simulation study was carried out using the ns-3 simulator to show the problem of the HWMP based Smart Grid NANs and demonstrate the advantage of the proposed scheme.

I. INTRODUCTION

Smart Grid is an integrated system that aims to control the energy consumption and renewable energies as well as the integration of the latter within the existing power transmission and distribution systems for the consideration of social problems such as global warming and increasing carbon emissions [1]. It combines the electrical grid and information and communications technology (ICT), enabling the interaction between energy suppliers and consumers by providing two way communications between them. The communication technologies play an extremely important role in Smart Grid networks which determine the grid efficiency.

Characterised by wide geographic area and different density of devices, the Smart Grid networks are usually described by a hierarchical three layer framework [2], consisting of home area networks (HANs), neighbourhood area networks (NANs) and wide area networks (WANs). Compared to the other two layers, the NANs are more complicated which involves majority of devices along with complex terrain. The Smart Grid NANs fulfil the communication gap between the WANs and HANs by providing power distribution with the ability of monitoring and controlling electricity delivery to households [3]. Therefore, the energy consumption information as well as other related information collected from each household should be delivered to the control centre in a timely and accurate manner. However, the data collection efficiency highly depends on the communication architecture and technologies used. Among various communication technologies, the wireless mesh network (WMN) is highly recommended for

Smart Grid NANs since it is capable of self organization, self configuration, self healing and multi-hop transmission [4].

Since the fundamental application of Smart Grid is data collection, most of the data flows happen between home appliances and control centres which is a multipoint to point (MP2P) or point to multipoint (P2MP) structure. Recently, the IEEE 802.11s group extended multi-hop mesh techniques to specify the same functionality of a wireless distribution system that interconnects 802.11 devices [5]. It provides frame forwarding and path selection at layer 2, supporting unicast, multicast and broadcast data delivery. Moreover, a tree based hybrid wireless mesh protocol (HWMP) is specified by the IEEE 802.11s standard which combines the on demand reactive and proactive routing protocols. The proactive mode maintains the routing state while the reactive mode deals with the topology change or link break. Therefore, the HWMP protocol is considered suitable for static mesh networks which is a characteristic of Smart Grid NANs. But, further improvements are essential for better supporting Smart Grid applications and guaranteeing quality of service (QoS) requirements.

Among multiple communication requirements, end-to-end delay is a most important performance that indicates the QoS for the communication and networking technology used in the Smart Grid, ranging from power generation and transmission, distribution to the customer applications [6]. The Smart Grid NANs will offer communications for a large number of devices spread over a wide area with satisfied communication requirements. However, most research to date has focused on improving the overall average end-to-end delay performance which ignores the impact of the communication technologies to each user. All the users in the Smart Grid should be serviced with guaranteed QoS. In [7], the author improved the fairness problem in the 802.11s mesh network by proposing a fair share algorithm (FSA) which allows node to adapt different packet sizes and various contention windows according to the location and traffic load. Nevertheless, the scenario used in the work does not show the impact of the routing protocol upon the network performance.

Due to the feature of HWMP, activating reactive mode when route is unavailable in the routing table, some nodes will suffer intermittent increased delay. We analyse the route unavailable problem as well as its impact and propose a static characterized HWMP for Smart Grid NANs based on the assumption that all the devices involved in the network are static. The proposed scheme aims to mitigate the route unavailable problem, simultaneously enhancing the delay performance of

the entire network. It includes two primary modifications to the original HWMP, an extended routing table and a historical path selection algorithm. The main achievements by applying the proposed scheme are 1) mitigated frequency of path discovery procedure which reduces delay caused by waiting for route response and network overheads and, 2) less collisions between data frames and path request (PREQ) messages leads to improved packet delivery ratio. The proposed scheme is evaluated using the ns-3 simulator.

II. HWMP REVIEW AND PROBLEM STATEMENT

The proactive HWMP specified in the IEEE 802.11s standard includes two operation modes, proactive PREQ and root announcement (RANN). Both of them construct the mesh networks in tree topology, yet the former mode produces less network overheads than the latter. Hence, the proactive PREQ mode is considered throughout this paper.

A. HWMP Review

In the proactive PREQ mechanism, the node configured as the root periodically broadcasts PREQ messages into the mesh network with the target being the broadcast address. Upon reception, each node creates or updates its forwarding path towards the root according to the information contained in the PREQ (e.g. link metric, sequence number). Afterwards, the node will forward the updated PREQ with cumulated ALM to its neighbours. Thus, the paths from all mesh stations towards the root are created. On the other hand, the PREQ messages contain a proactive path reply flag which determines whether a node has to reply with a path reply (PREP) message in order to build the inverse path. Consequently, the bidirectional paths between all mesh stations and root are available. The default link metric defined in the IEEE 802.11s standard named airtime link metric (ALM) is calculated by the following equation [8]:

$$C_a = [O + B_t/r] * \frac{1}{1 - e_f} \quad (1)$$

where O and r are the channel access overhead and data rate respectively, depending on the type of PHY layer model used. B_t is the size of the transmission frame and e_f is the frame error rate.

According to [9], each node in the HWMP constructed mesh networks maintains a routing table that stores the route information for packet forwarding. The routing table is updated if and only if the received PREQ contains a better link metric than the current route. In proactive PREQ mode, only one optimal route towards the root is maintained in the routing table that represents the minimum delay path. When a node has a packet to transmit (either one that it has generated itself or one which it is relaying for another), it checks the path from the routing table first. If there exists the available path to the root, the packet will be inserted to the queue or transmitted through the available path. Otherwise, the reactive mode will be activated for route discovery by broadcasting a PREQ message. The destination node will respond by replying with a unicast PREP message to the source node.

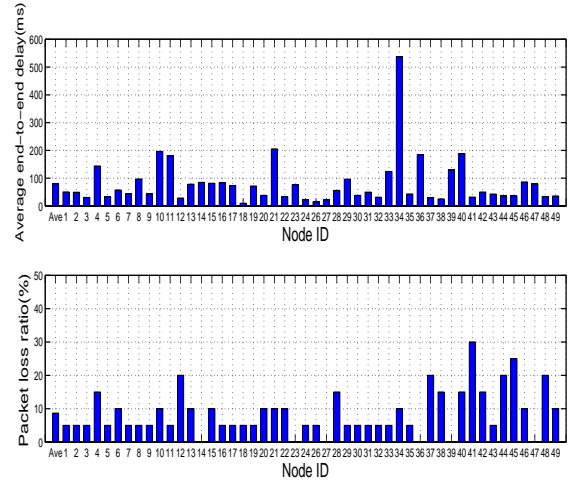


Fig. 1: Average end-to-end delay and packet loss ratio for entire network and each node

B. Problem statement

In Smart Grid, the electrical related status (e.g. energy consumption) is collected by the electronic devices (e.g. smart meter), then transmitted to the control centre through NANs for monitoring and analysing. Meanwhile, control messages, feedback or billing information are unicast or broadcast from the control centre to the customer side. This information is required to be delivered within a certain latency range as well as acceptable reliability. As a matter of fact, most research focused on the overall average end-to-end delay which ignores the situation of individual nodes. However, the Smart Grid networks are expected to provide each user with satisfied information delivery [6]. In order to demonstrate the impact of HWMP to each user, the simulation was conducted by using the ns-3 simulator. We have configured a simple grid topology, including 49 nodes with the root node in the centre. As a data collection network, the upstream traffic is considered in the paper. All nodes generate constant bit rate (CBR) traffic towards the root node in a periodic manner which is 1 packet per minute. Other simulation settings will be explained in Section IV.

Figure 1 shows one of the results in multiple random simulations (different seeds), representing the average end-to-end delay and packet loss ratio of the entire network and each node, respectively. In both column charts, the first column is the average performance from overall situation while the others indicate each individual node. Generally speaking, most of nodes have less delay than the average and high reliability over 90%. However, we can observe that some nodes experience relatively high delay (in excess of 100 ms) and node 34 even has delay more than 500 ms, although its packet loss ratio is not high. Moreover, it is worth noting that the delay of the farthest node 49 (hop count) is lower than the average. This is caused by the path discovery procedure when no route is available. And the PREQ messages triggered by path discovery are very likely to suffer collision and retransmission which will bring further unexpected delay. To mitigate this problem, we give a simple solution by considering the static characteristic of the Smart Grid networks.

TABLE I: Routing table for each mesh station

Mesh Station	Destination	Sequence Number	Next Hop	ALM	Hop Count	Lifetime
STA A	MAC address R	MAC R sequence number	MAC address R	metric AR	1	lifetime
STA B	MAC address R	MAC R sequence number	MAC address A	metric AR + metric BA	2	lifetime
STA C	MAC address R	MAC R sequence number	MAC address B	metric AR + metric BA + metric CB	3	lifetime

TABLE II: Historical routing table for mesh station C

Destination	Sequence Number	Next Hop	ALM	Hop Count	Lifetime
MAC address R	MAC R sequence number	MAC address B	metric AR + metric BA + metric CB	3	lifetime
Destination	Sequence Number	Next Hop	Total Retransmission Time*	Hop Count	# of transmitted packets*
MAC address R	MAC R sequence number	MAC address B	10	3	6
MAC address R	MAC R sequence number	MAC address D	8	3	7
MAC address R	MAC R sequence number	MAC address E	12	3	5

III. STATIC CHARACTERIZED HWMP

The proposed scheme aims to improve the intermittent route unavailable problem by using two methods, based on an extended routing table and a historical path selection algorithm. The first method extends the original routing table for recording the information of the path used (e.g. retransmission time), while the second method suggests a path selection algorithm based on the recorded information when no active route is available. But bear in mind that the proposed scheme is based on a reasonable assumption that all the devices involved in the mesh networks are static. Therefore, all the neighbouring nodes are always within the transmission range unless they are malfunctioning or their power is switched off.

A. Routing Table Extension

The proactive routing table of HWMP stores the information for packets forwarding towards the root, including the root and next hop mac addresses, ALM, hop count and route lifetime. Figure 2 shows a simple example of the path construction procedure by using proactive PREQ messages while Table 1 is an example of a corresponding proactive routing table for each mesh station towards the root. Similarly, the reverse path is stored and updated after receiving the unicast PREP message. If a node can not find the route towards the root for the holding packet, the PREQ message will be broadcast for path discovery. After receiving PREP, the new route is stored in the reactive routing table for the current and following packets before the next fresh proactive PREQ.

On the other hand, the default interval between two successive proactive PREQs and the lifetime of proactive route information are 2 and 5 seconds, respectively. However, before the lifetime expires, there is a certain probability that no fresh proactive PREQ message is received. This is caused by two

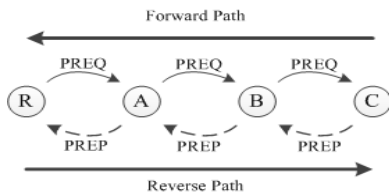


Fig. 2: Proactive PREQ path formation

main reasons, 1) PREQs discard if the contained ALM is worse than the current maintained one and, 2) collisions between data frames and PREQs. Both of them lead to the route unavailability problem when a node has packet a to transmit. In order to take advantage of the static characteristic of Smart Grid networks and improve the route availability, the original routing table is extended to record the information of the used paths and is named 'historical routing table', as shown in Table 2. This table shows an example of the historical routing table of mesh station C by assuming two more used paths with next hop of station D and E, including historical routing table and the original for comparison.

By contrast with the original routing table, only two fields in the historical routing table are different. More specifically, the total MAC layer retransmission time and number of transmitted packets of each route are recorded instead of ALM and lifetime. The ALM is a periodic and cumulated link metric of route from the source to the destination, while the lifetime is the time of validity of ALM. The former information takes into account each link through the path which is not useful for the historical path selection algorithm due to frequent route change. Because the information of the used paths might be used at any time, thus there is no lifetime for the historical routing table. Similar to ALM, the historical routing table is updated by accumulating the MAC layer retransmission time and number of transmitted packets after each packet transmission.

B. Historical Path Selection Algorithm

The original proactive mode will search the proactive routing table first, followed by reactive routing table. If both routing tables are not available, the path discovery procedure will be executed by broadcasting a PREQ message. Based on the historical routing table, the node has an extra opportunity to find a route before path discovery by using the historical path selection algorithm. This method is launched when both proactive and reactive routing tables are not available, as shown in Figure 3. The main idea of the proposed mechanism is to find the optimal link to the neighbouring node for the node without an available route. Then the neighbouring node will relay the packet according to its routing table.

In the IEEE 802.11s standard, the calculation of link error rate is not described. Thus, we adopt the method for calculating the link error rate of the current link introduced in [10] which

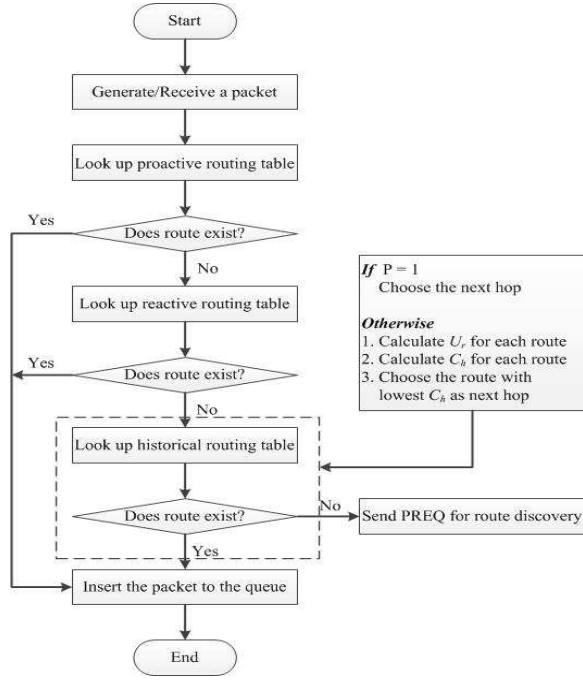


Fig. 3: Path selection procedure flow chart

uses the number of attempted retransmissions to deliver a data frame, as shown in the following:

$$e_f = \frac{\frac{1}{N} \sum_{i=1}^N M_i}{R} \quad (2)$$

Where N is the total number of transmitted packets during a PREQ interval, M_i is the number of retransmissions required for packet i and R is the maximum allowed retransmission attempts. This calculation method takes into account the Smart Grid environment, in which most data transmission is upstream. Hence, the link error rate can only be calculated by unicast data transmission.

Since the default link metric adopted in HWMP is ALM, the proposed historical route selection method follows the same rules. The main difference is that the proposed method only considers one hop to the neighbouring node which will relay the packet according to its routing table. Before deriving the historical ALM for the proposed scheme, we need to introduce the utilization ratio (U_r) which indicates the usage frequency of each route. For instance, mesh station C has three used paths P_1 , P_2 and P_3 with link error rate $e_1 = 0$, $e_2 = 0.1$ and $e_3 = 0.2$, respectively. It seems the path P_1 with low packet loss ratio is better than the other two paths. However, if path P_1 is only used for once while the used time of the other two paths are much more than P_1 , it can not demonstrate that the path P_1 is the best. Denoting the total number of recorded historical paths as K , the utilization ratio can be calculated by the following equation:

$$U_r^j = \frac{\tilde{N}_j}{\sum_{j=1}^K \tilde{N}_j} \quad (3)$$

Then we introduce a simple historical ALM calculation method, which assigns different weight to each path according

to the utilization ratio. Denoting the total number of transmitted packets and the retransmission time of used path P_j as \tilde{N}_j and \tilde{M}_j , respectively. The historical path ALM C_h can be calculated by the following equations:

$$C_h^j = [O + B_t/r] * \frac{1}{1 - e_j} * \frac{1}{U_r^j} \quad (4)$$

and

$$e_j = \frac{\tilde{M}_j}{\tilde{N}_j * R} \quad (5)$$

By applying this path selection algorithm along with historical routing table, each node can get an extra opportunity to find a path towards the root before route discovery. Moreover, this route also can be used for the following packets before receiving fresh PREQ messages. Consequently, the intermittent increased delay of individual nodes can be reduced and the overall network performance is improved.

IV. PERFORMANCE EVALUATION

The performance of the proposed scheme is evaluated by using the ns-3 simulator which is a discrete network simulator. In the simulation, the 802.11b PHY layer is configured with maximum transmission rate as 2 Mb/s and the MAC layer uses the basic distributed coordination function (DCF) channel access mechanism based on the carrier sense multiple access with collision avoidance (CSMA/CA). Each node in the mesh network represents an electrical device (e.g. smart meter) in Smart Grid NANs. Advanced metering infrastructure (AMI) is a fundamental application in the Smart Grid networks, thus the typical meter reading data collected in a periodic manner with 125 bytes packet size [11] is used in the simulation. In this paper, we focus on the two primary performance indicators for the Smart Grid networks, end-to-end delay and packet delivery ratio.

Firstly, we inspect the impact of the proposed scheme upon the individual nodes in the scenario used in Figure 1.

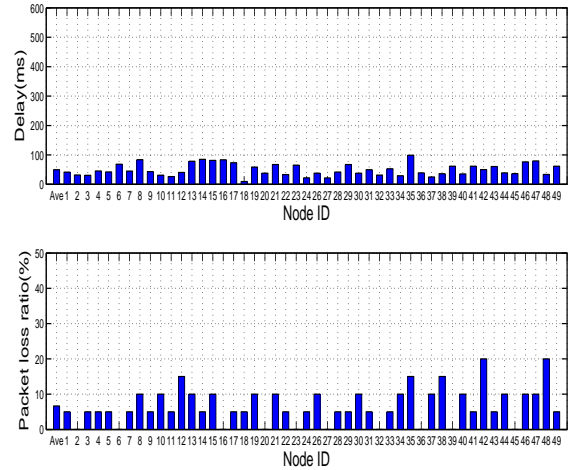


Fig. 4: Average end-to-end delay and packet loss ratio for entire network and each node of the proposed scheme

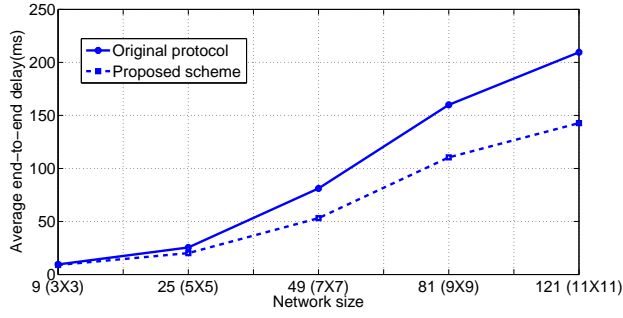


Fig. 5: Average end-to-end delay

All parameter settings are in accordance with the previous simulation. Figure 4 shows the performance of the proposed scheme, in which we can observe that the majority of nodes have improved average end-to-end delay and all nodes have the delay below 100 ms. In general, some nodes with high delay (e.g. node 34 in Figure 1) have been greatly improved by applying the proposed scheme, while a few nodes suffer increased delay but within an acceptable range. The latter phenomenon happens due to the changed transmission strategy of other nodes which may cause collision and queuing. Furthermore, the packet delivery ratio of the proposed scheme is slightly better than the original protocol.

The following simulations show the impact of the proposed scheme to the entire Smart Grid network with different network sizes. All scenarios are configured with the root in the center of the grid topology by using 9, 25, 49, 81, 121 nodes and all leaf nodes generate constant bit rate (CBR) packets towards the root. Figure 5 indicates the average end-to-end delay between the proposed scheme and the traditional HWMP protocol. As the network size enlarges, both methods show increased delay. However, the increasing trend of the proposed scheme is slower than the original protocol, especially when more nodes are deployed in the network. This is because the increased collision of PREQ messages leads to more route discovery procedure as well as collision within the procedure. Thus packets have to wait more time for the available route before being inserted to the queue.

Although the primary purpose of the proposed scheme is to improve the end-to-end delay of HWMP protocol in Smart Grid environment, a better packet delivery ratio also can be achieved. As shown in Figure 6, the proposed scheme shows better packet delivery ratio than the original protocol. This benefit arises from the reduced network overheads created by the path discovery procedure. Since more and more nodes are deployed in the network, the collision between PREQs or data frames and PREQs increases which will cause a degraded packet delivery ratio. By applying the proposed scheme, not only the unnecessary delay brought by path discovery can be reduced, but also the reliability is improved.

V. CONCLUSION

The IEEE 802.11s standard based wireless mesh networks can provide the functionality of a wireless distribution system and reliable data transmission for the Smart Grid NANs. However, it is essential to mitigate the route unavailable

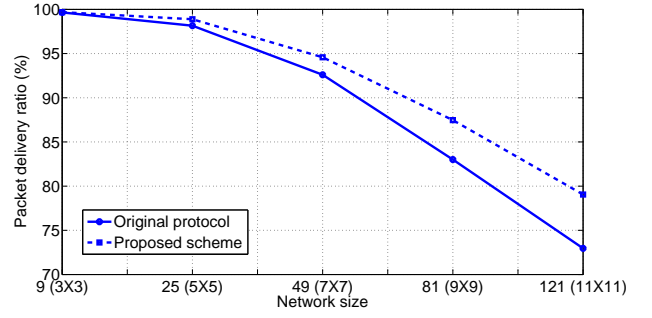


Fig. 6: Packet delivery ratio

problem, which causes intermittent increased delay to packet transmissions. Based on the static feature, we propose a static characterized HWMP for deploying multi hop mesh networks in Smart Grid NANs. The simulation results indicate that the proposed scheme achieves better route availability and reduces delay by about 30% compared to the original protocol. Moreover, the packet delivery ratio is also improved slightly.

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